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The classification of errors involved in the determination of chances of hit, and the evaluation of chance hit with Centurion under quasi-battle conditions

1

Incl #1 OC/AA/3-1610

R. W. Shephard

S. A. Beach

OC/43403

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Fort Halstead
Kent. Regd #12475

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February
1958

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1. Errors.

2. Guns, QF 20 pr.

3.

4.

5.

ADDED ENTRIES

I HESH shell

II Shephard, R. W.

III Beech, S. A.

IV

V Project No.

VI Contract No.

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The classification of errors involved in the determination of chances of hit, and the evaluation of chance of hit with Centurion under quasi-battle conditions

5

R. W. Shephard (B5)

S. A. Beach (B5)

6 Feb 1958

Summary

This report gives a list of the component errors to be used in chance of hit calculations, and discusses the magnitude of these errors for the QF 20 pr gun in Centurion firing APDS Mk 4 shot and a fictitious HESH shell. Using these data, the chances of hit to be expected under quasi-battle conditions are evaluated.

Approved for issue:

Ewen M'Ewen, [redacted]tor

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INTRODUCTION

1. As a result of discussions held during the First and Second Tripartite Technical Conferences on Tank Armament, held in 1956 and 1957, Panel C (Assessment) was able to reach a considerable measure of agreement on the subject of chance of hit with tank and anti-tank guns.

2. Details of the discussions are given in Annexure 3 of "Report of Tripartite Conference on Medium Tank Armament 1956" (1)*. In particular, the following agreement between UK, US and Canada is tabled:

> "IT WAS AGREED that the component errors which enter into chance of hit calculations should be listed. The list should be split into three parts corresponding to:-
>
> (a) Permanent biases (or fixed biases)
>
> These are errors which affect the position of the MPI (Mean Point of Impact) and remain the same from occasion to occasion.
>
> (b) Variable biases
>
> These are errors which affect the position of the MPI but vary from occasion to occasion.
>
> (c) Random errors or dispersions
>
> These are errors which affect the dispersion of the rounds about the MPI.
>
> When each country had prepared its list, the lists should be checked against one another".

3. US were able to put forward at the time a list of component errors classified in the agreed manner; this list has since been published(2). The present paper gives a list that has received general UK approval, and, on the basis of this, the chances of hit to be expected with the 20 pr gun in Centurion are evaluated. It is hoped that this evaluation will prove a ready guide to the method in which chances of hit under quasi-battle conditions are calculated, and will also provide a general reference to the magnitude of certain of the errors involved.

LIST OF ERRORS AND THEIR DEFINITIONS

Component errors in chance of hit calculations

4. Table 1 lists the errors that enter into calculations of chances of hit with tank and anti-tank guns under "quasi-battle conditions".

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* Numbers refer to references at end of Report

Table 1

Classification of component errors

Class	Errors in elevation	Errors in line
PERMANENT BIASES	Mean jump Sight off-set Errors in range-graduation (sight or drum) Bias in rangefinding	Mean throw-off Sight off-set Drift
VARIABLE BIASES	Shooting-in error Alignment error Mechanical errors & biases in sighting system and linkage Jump, occasion-to-occasion Droop, occasion-to-occasion Ballistic coefficient, effect of var'n in air density Gunwear, effect on MV Charge temp, occasion-to-occasion Head-wind Range-finding error Error due to discrete range intervals	Shooting-in error Alignment error Throw-off, occasion-to-occasion Lateral bend, occasion-to-occasion Trunnion tilt, occasion-to occasion Cross-wind) and/or errors resulting from attempted correction of these
RANDOM ERRORS OR DISPERSIONS	Ballistic error (intrinsic dispersion of gun and ammunition) which includes:- Jump, rd-to-rd Droop, rd-to-rd Yaw, rd-to-rd Ballistic coefficient, rd-to-rd Variation in MV, rd-to-rd Propellant, lot-to-lot var'n Charge Temp, rd-to-rd Lay, rd-to-rd var'n Backlash in sight/gun system Gustiness in head-wind	Ballistic error, which includes:- Throw-off, rd-to-rd Lateral bend, rd-to-rd Yaw, rd-to-rd Lay, rd-to-rd var'n Backlash in sight/gun system Gustiness in cross-wind

5. In the remainder of this section, the errors listed above will be defined and described.

Permanent biases (or fixed biases)

6. These are errors that affect the position of the MPI (Mean Point of Impact) and remain the same from occasion-to-occasion and from tank-to-tank, or anti-tank gun to anti-tank gun.

7. Permanent biases arise principally from inherent limitations in the fire-control system or from differences between the conditions of zeroing and the conditions under which rounds are fired in anger. Thus an error in mean jump may arise if rounds used for zeroing and those fired in action are of different types. There will be errors due to sight-offset and drift if the target engaged in action is at a different range from that at which zeroing was carried out; the total of these errors is equal to the distance between the line of sight and the mean trajectory at the range under consideration for a correctly zeroed gun. Other permanent biases are self-explanatory: errors in range-graduation in the sight graticule or on the range-drum, and the bias in the rangefinder or other range-finding device that may be used.

Variable biases

8. These are errors that affect the position of the MPI, but vary in magnitude from engagement-to-engagement (occasion-to-occasion), or from tank-to-tank or anti-tank gun to anti-tank gun; they are constant during any particular engagement.

9. The most important component error of the variable biases is the shooting-in error, which results from the combination of a zeroing error with an alignment error. These errors arise in the following manner. There exists, for most guns, a drill whereby the axes of the sight and gun can be aligned using a purely mechanical or optical method. A typical example of this drill would be one in which the gun was bore-sighted on to a distinct point on a distant target and the sight was then adjusted relative to the gun until it also was sighted on to the same point. This process corresponds, in effect, to fixing an origin for the sight from which other adjustments are made. The error involved in carrying out this procedure is termed the alignment error.

10. The axis of the gun with which the sight has been aligned (usually either the apparent axis or the muzzle axis) and the mean line of departure of the shot may not coincide; in order therefore that the sight can be aligned with the mean line of departure it is necessary to determine some position correction (zeroing correction) that can be applied to the sight after alignment. Colloquially, the sight should then be pointing where the shot goes. The drill whereby this is achieved is known as zeroing; it is carried out at least once during the life of the gun. A desirable zeroing drill is as follows. A square target is set up at a surveyed range, and gun and sight are then aligned as described above. Tangent elevation, corresponding to the target range, is then applied to the gun using the range-drum and a cleaner round fired (not at the target). The sight is layed on the centre of the target and one round fired; the sight is relayed and another round fired, and this procedure is repeated until several (say, total 3) rounds have been fired. The MPI of the group is determined. The sight is relayed on the centre of the target, and then adjusted relative to the gun on to the MPI of the group; a confirming round may be fired. The amount of this adjustment is noted, and is named the zeroing correction. There are naturally inaccuracies in this procedure due to human and mechanical errors in laying, sighting, etc., and to the fact that only a limited number of rounds is fired to determine the MPI; the total of these errors is known as the zeroing error. The combination of this error with the alignment error, which gives the total error in the zeroing correction, is known as the shooting-in error.

11. The gun and sight are normally aligned each day, or on each occasion that the weapon is moved to a new site; as has been mentioned previously, however, the zeroing correction which is applied subsequent to each alignment procedure is only determined infrequently.* Thus in a particular engagement both alignment and shooting-in errors will be present. Values of these errors are normally estimated in practice by determining experimentally the magnitude of the various component errors and then compounding them according to the precise drill procedure adopted(3).

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* It should be noted that, if a silent zeroing technique is adopted, zeroing can be carried out much more frequently than has been usual in the past.

12. The remaining variable biases are relatively simpler to describe. Occasion-to-occasion variations in jump and droop affect the mean trajectory in elevation, and variations in throw-off and bend affect it in line; allowance must be made for the differences between the values of these parameters on the occasion the gun was zeroed, and their values during the engagement of an enemy target. Similarly, an error in elevation arises from variations in ballistic coefficient due to differences in air density, and from the effects on muzzle velocity of changes, from the conditions of zeroing, of gun wear and charge temperature; in line, occasion-to-occasion variation in trunnion tilt (and/or errors resulting from an attempted correction) will cause biases during an engagement, again because of the differences between the conditions during the engagement and those under which zeroing was carried out. Head-wind and cross-wind also cause differences in the mean trajectory on different occasions.

13. In any particular engagement an error arises due to rangefinding; that is to say, the range that is set initially on the range-drum or sight graticule is usually inaccurate (even if a rangefinder is used). A small error also arises because the range drum or sight graticule is often engraved only in discrete range intervals and ranges thus have to be taken to the nearest increment.

14. It must be noted that many of the errors mentioned above are often grouped under the general term "non-retention of zeroing". Further, it should be mentioned that it is assumed in this paper that a cleaner round is always fired some time before an engagement starts since it is not considered feasible to attempt to take account of the erratic behaviour that is often observed with such a round.

Random errors or dispersions

15. These are the errors that affect the dispersion of individual rounds about the MPI.

16. The most important error in this category is the ballistic error. It includes, in addition to variations due to windage and to difference in projectile weights within the permitted design tolerances, inaccuracies due to round-to-round variations of jump, droop, yaw, ballistic coefficient and muzzle velocity in elevation, and due to throw-off, lateral bend, and yaw in line. In most British tank and anti-tank gun ammunition, propellant lots are mixed; dispersion in elevation is increased by attendant lot-to-lot variations due in part to errors in charge adjustment. Similarly, round-to-round variation in charge temperature increases dispersion in elevation.

17. In addition to the ballistic factors mentioned above, dispersion is affected by round-to-round variations in lay, by backlash in the sight/gun system, and by gustiness in head or cross-wind.

Comments

18. One brief comment may be made on the list of errors given above. It should be noted that not all the errors mentioned are necessarily present with every weapon or on all firings. Conversely, the list is not necessarily exhaustive, though it is thought to contain all the major errors. It should therefore be regarded primarily as an aide-memoire to component errors when chance of hit calculations are to be carried out.

19. In the following section, the magnitude of errors listed above will be investigated, with particular reference to the Centurion tank equipped with 20 pr QF gun. A typical calculation of chance of hit under quasi-battle conditions will subsequently be made using the values obtained.

20. It has been found that, in spite of the many papers that have been written on accuracy of tank gunnery (the list of references at the end of this report, which is by no means exhaustive, is an indication of the amount of work that has been carried out), it is difficult to obtain really satisfactory estimates of many of the errors considered. The values quoted here, however, are thought to be the best at present available, even though, in many instances, it has been necessary to carry out quite large extrapolations from data for other ammunition or obtained under circumstances differing from those under consideration.

21. All values for errors given in this paper have been expressed as angles at the gun in mils (6400m̸ = 360°) and also, for convenience, in minutes of arc. Errors with values less than about 0.003m̸ have in general been considered negligible.

MAGNITUDE OF COMPONENT ERRORS FOR CENTURION

Gun and projectile parameters

22. Chances of hit will eventually be calculated for both APDS Mk 4, and a fictitious HESH round, fired from a 20 pr gun mounted in Centurion tank. The relevant characteristics taken for both these projectiles are given in Table 2 below:-

Table 2

Characteristics of 20 pr projectiles

Projectile		20 pr APDS Mk 4	20 pr HESH
Muzzle velocity		4800 ft/sec	2600 ft/sec
Ballistic coefficient		1.43 (1940 law)	1.50 (1910 law)
Angle of Projection for:-	500 yards	1.095m̸ (3.695')	3.934m̸ (13.278')
	1000 yards	2.263m̸ (7.636')	8.572m̸ (28.930')
	1500 yards	3.481m̸ (11.748')	14.097m̸ (47.576')
	2000 yards	4.787m̸ (16.156')	20.740m̸ (69.995')
Angle of descent for:-	500 yards	1.125m̸ (3.798')	4.257m̸ (14.366')
	1000 yards	2.393m̸ (8.075')	9.759m̸ (32.937')
	1500 yards	3.791m̸ (12.793')	18.118m̸ (61.147')
	2000 yards	5.364m̸ (18.103')	29.177m̸ (98.471')

Permanent biases

23. Mean jump and throw-off. These biases are equal to the differences between the mean jump and throw-off of the ammunition used for zeroing and those for the ammunition fired in anger. No measurements have yet been made of the jump and throw-off of 20 pr APDS Mk 4; and in fact little is known about the causes of these errors (4)(5). It seems reasonable however for present purposes to assume that the jump and throw-off for APDS Mk 4 are the same as those that have been measured for APDS Mk 1; similarly it has been assumed that a HESH shell in 20 pr would have the same jump and throw-off as the 20 pr HE Mk 1 shell (6) which also has a low velocity.

Table 3

Jump and throw-off for 20 pr

Projectile	Jump	Throw-off
APDS Mk 4	-0.822m̸ (-2.775')	L0.100m̸ (L0.338')
HESH	-0.874m̸ (-2.950')	R0.063m̸ (R0.212')
Difference	0.052m̸ (0.175')	0.163m̸ (0.550')

It is assumed in this report that the gun is zeroed by firing APDS Mk 4 (see Appx A). The biases due to mean jump and throw-off will therefore have values of zero when APDS is fired in anger, and values of -0.052m̸ (-0.175') and R0.163m̸ (R0.550') respectively for HESH.

24. Sight off-set. The sight in Centurion is 22.5 inches higher, and 26.5 inches to the right of the axis of the gun at the trunnions. The bias due to sight-offset has been calculated accordingly and is given in the following table; zeroing has been assumed to be carried out at 1000 yards range, and the effect of the normal practice of adjusting the telescope 1 minute right to make some allowance for drift (see Para 27 below) has been included.

Table 4

Bias due to sight off-set

Range	Bias in elevation	Bias in line
500 yards	-0.637m̸(-2.149')	L1.046m̸(L3.530')
1000 yards	0	L0.296m̸(L1.000')
1500 yards	+0.212m̸(+0.716')	L0.047m̸(L0.157')
2000 yards	+0.318m̸(+1.074')	R0.079m̸(R0.265')

25. Error in range-graduation This error is assumed to be negligibly small for Centurion; the range-drum is engraved using the best possible data from R and A firings. Divergencies in an actual gun from range table values, due to factors such as gun wear, charge temperature differences and so on, are considered below.

26. Bias in rangefinding It is generally assumed as a result of work carried out to date (7)(8)(9)(10)(11)(12)(13) that the grand mean of ranges estimated either visually or using a rangefinder, taken over all operators and over all occasions coincides with the true range. No trials have, however, been carried out specifically in UK to test whether this is true, and there is some information from US sources (2) which indicates values for biases in both methods of rangefinding. The situation is complicated by the fact that a bias may exist for a particular operator on a particular occasion (13), and this implies an elaborate trials programme to ensure that a reliable estimate is obtained for the permanent bias under consideration here, which covers all operators on all occasions. Until more information becomes available, it will be assumed for the purposes of this paper that the bias due to rangefinding is negligible for both visual and rangefinder range determination.

27. Drift. Even when there is no cross-wind, a shell does not remain in the vertical plane of fire; the distance by which it falls away from the plane of departure is called the drift and has a value, $\theta \tan \phi$ mins, where θ is the drift coefficient in minutes of arc and ϕ the tangent elevation; θ is taken to have the value 160 for the 20 pr HESH shell and 120 for the 20 pr APDS Mk 4 shell. Normal RAC gunnery practice is to first make the zeroing correction, which includes the effect of drift of the APDS shell at 1000 yards, and then adjust the telescope graticule one minute right to make some allowance for the drift at the longer ranges with lower velocity shells. The effect of this correction has already been included in the calculation of the bias due to sight off-set (para 24); the remaining bias due to drift, for both the shells considered, is given in Table 5:-

Table 5

Bias due to drift for 20 pr tank gun shells

Range	20 pr APDS Mk 4	20 pr HESH
500 yards	L0.041m̸(L0.138')	R0.104m̸(R0.351')
1000 yards	0	R0.320m̸(R1.079')
1500 yards	R0.043m̸(R0.143')	R0.577m̸(R1.947')
2000 yards	R0.087m̸(R0.296')	R0.886m̸(R2.991')

Variable biases

28. Shooting-in error The derivation of this error from various component errors based on the drill normally adopted when shooting-in the 20 pr in Centurion is described in Appendix A. The following values are given:-

Shooting-in error in elevation = 0.516m̸(1.741')sd

Shooting-in error in line = 0.455m̸(1.536')sd

29. Alignment error Values for this error are derived in Appendix A also; details of the results are given below:-

Alignment error in elevation = 0.337m̸(1.137')sd

Alignment error in line = 0.345m̸(1.164')sd

30. Mechanical errors and biases in sighting system and linkage These errors arise from two main causes:-

(a) inaccuracies in the sight-gun linkage set-up and geometry; these errors together are taken as 0.044m̸(0.150')sd for Centurion, based on measurements on Centurion 2(14);

(b) inaccuracy in engraving the range-scale; the tolerance limits on the scale on the range-drum in Centurion are ±0.005 inch per inch of scale (1" scale = 11.48m̸ (39.57')); it is assumed here that there is a Gaussian distribution of errors between these extreme values.

The total error due to these causes is given in Table 6 below

Table 6

Errors in sighting system and linkage

Range	20 pr APDS Mk 4	20 pr HESH
500 yards	0.045m̸(0.151') sd	0.045m̸(0.153')sd
1000 yards	0.044m̸(0.150') sd	0.055m̸(0.184')sd
1500 yards	0.045m̸(0.151') sd	0.074m̸(0.250')sd
2000 yards	0.046m̸(0.156') sd	0.103m̸(0.346')sd

31. Occasion-to-occasion variation in jump and throw-off There is evidence that there is no variation in the mean jump or throw-off of the 20 pr gun firing APDS Mk 1 and HE Mk 1 shell from occasion-to-occasion or series-to-series (6)(19). It is assumed here therefore that these errors are also negligible for 20 pr APDS Mk 4 and HESH ammunition.

32. Occasion-to-occasion variation in droop and lateral bend Major alterations to droop and lateral bend may occur due to changes in atmospheric conditions, particularly in a hot gun. For instance, a shower of rain, or freshening of the wind, have been found to alter droop and lateral bend. (8)(20)(21) Values for these errors, which include variations between barrels, are therefore naturally difficult to obtain. A perusal of the references noted above however suggests that values of 0.296m̸ (1.000')sd for occasion-to-occasion variations in droop, and 0.074m̸ (0.250')sd for lateral bend are probably reasonable for present purposes.

33. Effect of variation in air density on ballistic coefficient Changes in air density due to alteration in air pressure, temperature and humidity cause roughly proportional changes in ballistic coefficient. Large variations can naturally occur from season to season and from theatre to theatre of operations. A range scale designed for 60°F will therefore have considerable errors at long ranges in cold or hot climates with lower velocity ammunition(22). No data have been found from which an estimate can be made of the change in air density that may occur from occasion-to-occasion. For the purposes of the present paper, however, it has been assumed that changes greater than 20% in air density from occasion-to-occasion (taken equivalent to an sd of 3% about the mean) are rare. On this basis the values determined for the error under consideration are given below:-

Table 7

Errors due to variation in ballistic coefficient

Range	20 pr APDS Mk 4	20 pr HESH
500 yards	0.002m̸(0.006')sd	0.013m̸(0.043')sd
1000 yards	0.005m̸(0.016')sd	0.050m̸(0.169')sd
1500 yards	0.011m̸(0.037')sd	0.127m̸(0.429')sd
2000 yards	0.021m̸(0.071')sd	0.271m̸(0.914')sd

34. <u>Effect of gun wear on muzzle velocity</u>. Gun wear causes an approximately linear drop in muzzle velocity over the life of the gun (19). Thus the muzzle velocity of a gun when it is fired in anger will be less than the velocity at which it was previously zeroed and there will be a corresponding drop in the MPI. A reasonable method of estimating the value of this bias is given in Appendix B; it is shown that the most likely value corresponds to a drop in muzzle velocity approximately $\frac{1}{4}$ of that expected over the total gun life. Firing trials carried out by ARDE have suggested that for 20 pr APDS Mk 4 ammunition the total drop in muzzle velocity over the gun life, of approximately 150 rounds, is 100 ft/sec. It is estimated that the drop for a 20 pr HESH round would be about 50 ft/sec from a new gun to a fully worn gun. The most likely biases in MPI calculated on the above basis are given in Table 8. Gun wear also affects the accuracy of rounds fired, ballistic dispersion increasing as the gun wears. Little is known, however, of the comparative size of this error component for the ammunitions under consideration here, and it has been thought sufficient in this paper to consider that the values for round-to-round dispersion given in paragraph 40 below are for a partly worn gun.

<u>Table 8</u>

<u>Bias due to gun wear</u>

Range	20 pr APDS Mk 4	20 pr HESH
500 yards	-0.013m/r(-0.044')	-0.082m/r(-0.278')
1000 yards	-0.025m/r(-0.084')	-0.183m/r(-0.619')
1500 yards	-0.040m/r(-0.135')	-0.308m/r(-1.038')
2000 yards	-0.055m/r(-0.184')	-0.465m/r(-1.568')

35. <u>Occasion-to-occasion variation in charge temperature</u>. It has not been found possible to trace any data giving directly the magnitude of this error. An indication of the size of possible changes in charge temperature may, however, be obtained from certain trials carried out by the Ordnance Board with 25 pr ammunition (23) and from conclusions reached by a Committee set up to investigate the accuracy of predicted fire from FBA guns (24). These suggest that, even if ammunition is not well insulated from atmospheric changes in temperature or from the sun's radiation, the diurnal variation in charge temperature is unlikely to exceed 20°F at the very most; in a tank it is likely that this variation will be much less. Little is known about the the season-to-season variation in charge temperature. However, if it is assumed that the tank's gun is zeroed in the same theatre of operations as that in which it is used in action, it would seem reasonable to take an sd of 5°F, say, as representing the variation in charge temperature likely to be encountered from occasion-to-occasion in tank guns. The angular effects of the corresponding changes in muzzle velocity are shown below; a temperature correction of 46ft/sec for 10°F has been taken for APDS and 4ft/sec for 10°F for HESH.

Table 9

Errors due to occasion-to-occasion variation in charge temperature

Range	20 pr APDS Mk 4	20 pr HESH
500 yards	0.008m (0.028') sd	0.005m (0.016') sd
1000 yards	0.016m (0.053') sd	0.010m (0.035') sd
1500 yards	0.027m (0.090') sd	0.017m (0.059') sd
2000 yards	0.036m (0.120') sd	0.026m (0.089') sd

36. Effects of trunnion tilt. It is obvious that a tank in battle will rarely take up a firing position in which it is perfectly level; in general therefore a trunnion tilt will be present. The Centurion is not equipped with a trunnion tilt corrector and the full effect of the tilt must be allowed for. Investigations into this source of error (25)(26)(27)(28) both in the UK and the US suggest that a value of 5° sd of trunnion tilt is reasonable for typical firing positions in action. It must be admitted that the data on which this value is based are not altogether satisfactory, and it is suggested that further work might well be undertaken to obtain reliable values for this important error. Values for the ammunitions under consideration are given in the following table:-

Table 10

Errors due to trunnion tilt

Range	20 pr APDS Mk 4	20 pr HESH
500 yards	0.094m (0.316') sd	0.337m (1.136') sd
1000 yards	0.194m (0.653') sd	0.733m (2.475') sd
1500 yards	0.298m (1.005') sd	1.206m (4.071') sd
2000 yards	0.410m (1.382') sd	1.775m (5.989') sd

When zeroing is being carried out more care can be taken in selecting a site and a value for trunnion tilt 1.0° sd for zeroing in the field is taken in Appendix A.

37. Head-wind and cross-wind. Recent work (29) has shown that the standard-deviations of head-wind and cross-wind velocity distributions in NW Europe each have values of 4.9ft/sec. It is not possible using the fire-control system in Centurion readily to allow for wind, and thus the full effects of the wind mentioned above must be taken into account; values are given below:-

Table 11

Effects of head-wind and cross-wind

Wind	Range	20 pr APDS Mk 4	20 pr HESH
Head	500 yards 1000 yards 1500 yards 2000 yards	All negligible	0.001/m(0.003')sd 0.004/m(0.014')sd 0.011/m(0.037')sd 0.025/m(0.084')sd
Cross	500 yards 1000 yards 1500 yards 2000 yards	0.010/m(0.034')sd 0.023/m(0.079')sd 0.033/m(0.112')sd 0.047/m(0.160')sd	0.120/m(0.404')sd 0.255/m(0.859')sd 0.399/m(1.348')sd 0.574/m(1.937')sd

38. Rangefinding error. Although there is some evidence that the errors in ranges estimated either visually or using a coincidence-type rangefinder are not normally distributed (13)(30), it is generally accepted that the divergence is slight and that a rangefinding error can be expressed with meaning in terms of a standard-deviation in the usual way (26). The following values are usually taken (31), based on experimental and trials' results (8)(11)(12)(13)(32)(33)(34)(35); figures for a rangefinder are included so that an estimate can be made later of the effects of incorporating a rangefinder in the fire-control equipment:-

Visual range estimation = 30% of range, sd

Rangefinder estimation (metre-base coincidence-type RF) = $19R^2$ yards sd, where R is the range in thousands of yards.

Values for these errors, expressed as angles at the gun, for the ammunitions under consideration are given in the following table:-

Table 12

Rangefinding errors

Method of determining range	Range	20 pr APDS Mk 4	20 pr HESH
Visual range estimation	500 yards 1000 yards 1500 yards 2000 yards	0.336/m(1.135')sd 0.709/m(2.394')sd 1.103/m(3.724')sd 1.554/m(5.244')sd	1.253/m(4.228')sd 2.873/m(9.695')sd 5.013/m(16.918')sd 7.827/m(26.417')sd
Metre-base rangefinder	500 yards 1000 yards 1500 yards 2000 yards	0.011/m(0.036')sd 0.048/m(0.162')sd 0.108/m(0.364')sd 0.202/m(0.682')sd	0.041/m(0.137')sd 0.192/m(0.647')sd 0.510/m(1.720')sd 1.096/m(3.699')sd

It should be noted that there is in fact no rangefinder on the Centurion tank; figures for errors in range determination using a rangefinder are however included so that estimates can be made later of the effects of including a rangefinder in the fire-control system.

39. Error due to discrete range intervals. A tank commander gives, in his fire order for opening fire, a range rounded off to the nearest 100 yards. (36). An error of as much as ± 50 yards may therefore be present from this drill*. The frequency distribution between these limits can be taken to be rectangular and represented as having a standard deviation of $100/\sqrt{12} = 28.9$ yards. The resulting magnitude of the error under consideration for the ammunitions concerned is shown in the table below:-

Table 13

Error due to discrete range intervals

Range	20 pr APDS Mk 4	20 pr HESH
500 yards	0.065/m(0.219') sd	0.241/m(0.815') sd
1000 yards	0.068/m(0.231') sd	0.277/m(0.934') sd
1500 yards	0.071/m(0.239') sd	0.322/m(1.087') sd
2000 yards	0.075/m(0.253') sd	0.377/m(1.272') sd

Random errors

40. Ballistic error. Recent accuracy firing trials with 20 pr APDS Mk 4 ammunition carried out by ARDE, indicate that the ballistic error (which includes the intrinsic dispersion of gun and ammunition, the effects of round-to-round dispersion in jump, throw-off, droop, lateral bend, yaw, ballistic coefficient and muzzle velocity) has a value of 0.276/m (0.93') sd in elevation and 0.246/m(0.83')sd in line at 1000 yards. These values have been taken to apply at all ranges, however, in this paper. It has also been assumed that the ballistic error for 20 pr HESH ammunition is 0.296/m (1.000')sd in both elevation and line at all ranges.

41. Lot-to-lot variation in propellant. APDS propellant for the 20 pr QF tank gun is, at present, proved to a pressure rather than, as is usual, to a velocity. Study of recent firings by CSR, as yet unpublished, show that, for 29 lots tested, the measured muzzle velocity had a standard deviation of 14.8ft/sec. This value has therefore been taken as representative of the error incurred by lot-to-lot variation in propellant for 20 pr APDS Mk 4. HESH propellants are proved, in the normal way, to a velocity, and figures of HESH shell firings indicate that a sd of 3ft/sec is reasonable to take for the variation to be expected from lot-to-lot for the fictitious 20 pr HESH shell. These errors are given, in Table 14 below, expressed as angular deviations at the gun:-

Table 14

Errors due to lot-to-lot variation in propellant

Range	20 pr APDS Mk 4	20 pr HESH
500 yards	0.008/m(0.027')sd	0.008/m(0.026')sd
1000 yards	0.014/m(0.048')sd	0.023/m(0.077')sd
1500 yards	0.024/m(0.081')sd	0.038/m(0.129')sd
2000 yards	0.033/m(0.111')sd	0.053/m(0.180')sd

* This error is the difference between the range ordered and the estimated range. The error between the estimated range and the true range is discussed in para 38 above.

42. Round-to-round variation in charge temperature. The results of trials carried out on Cromwell and Sherman tanks suggest that under normal operating conditions, the round-to-round variation in charge temperature is unlikely to exceed 2°F for rounds stowed in the turret and 5°F if rounds in the co-driver's position are included. It will be assumed that these variations are unlikely to be exceeded in the Centurion and a standard deviation of $1\frac{1}{2}$°F will be taken as typical. The temperature corrections given in para 35 are used to determine values given in the table below:-

Table 15

Errors due to round-to-round variation in charge temperature

Range	20 pr APDS Mk 4	20 pr HESH
500 yards	0.002m̸(0.008')sd	0.003m̸(0.009')sd
1000 yards	0.004m̸(0.014')sd	0.006m̸(0.019')sd
1500 yards	0.007m̸(0.025')sd	0.009m̸(0.031')sd
2000 yards	0.010m̸(0.034')sd	0.014m̸(0.047')sd

43. Round-to-round variation in lay. The accuracy with which a gunner can lay his sight on a tank target in battle is not known in detail. Although many values of laying errors have been determined from trials carried out on gunnery ranges against targets with well-defined aiming marks (37), the values obtained are certainly much smaller than those that would occur in haste in battle (26) against tank targets, which are less distinct and clear cut (38). It will be assumed here that a reasonable value of the round-to-round variation of lay in battle is 0.119m̸(0.40')sd in elevation and 0.148m̸ (0.50')sd in line. When laying against a distinct target, in for example the shooting-in drill, a value of 0.059m̸ (0.20')sd has been taken.

44. Backlash in sight/gun system. Although this error has been appreciable in some earlier tanks (12)(15)(16)(17) it is negligibly small for the Centurion (19) provided that the normal laying drill is adopted which is intended to eliminate the effects of backlash.

45. Gustiness in head-wind and cross-wind. The standard deviation of the distribution of gust velocity about the head-wind and cross-wind velocities (para 37) is 6.0ft/sec (29). The effect of these gusts is shown below for the projectiles under consideration:-

Table 16

Effects of gustiness in head-wind and cross-wind

Gusts	Range	20 pr APDS Mk 4	20 pr HESH
Head	500 yards	All negligible	0.001m̸(0.003')sd
	1000 yards		0.005m̸(0.017')sd
	1500 yards		0.013m̸(0.046')sd
	2000 yards		0.030m̸(0.102')sd
Cross	500 yards	0.012m̸(0.041')sd	0.145m̸(0.495')sd
	1000 yards	0.028m̸(0.096')sd	0.312m̸(1.052')sd
	1500 yards	0.041m̸(0.138')sd	0.489m̸(1.650')sd
	2000 yards	0.058m̸(0.196')sd	0.703m̸(2.372')sd

Summary

46. Values have now been given for Centurion of all the component errors, as listed in Table 1, which enter into chance of hit calculations. For convenience, the values are tabulated in Tables 18 to 21 inclusive, which are at the end of this report.

CHANCES OF HIT WITH CENTURION UNDER QUASI-BATTLE CONDITIONS

47. In this section, the results are given of calculations to determine the first round chance of hit under quasi-battle conditions for APDS Mk 4 and a fictitious HESH shell fired from the 20 pr tank gun in Centurion, at ranges of 500, 1000, 1500 and 2000 yards. The values of the component errors given in Tables 18 - 21 have been used, all of which enter into the calculation when chances of hit under quasi-battle conditions are required. It has been assumed (as is usual) that the total errors in line and elevation are sufficiently Gaussian in form to allow tables of the Normal error integral to be used, and that errors in line and elevation are uncorrelated.

48. Table 17 below gives values for chance of hit on a 7ft 6 ins square target* when visual range estimation is used. For the sake of comparison, values for chance of hit when a metre-base rangefinder is used are also given.

Table 17

First round chances of hit against a 7'6" square target with Centurion under quasi-battle conditions

Method of determining range	Range	Probability of hit	
		20 pr APDS Mk 4	20 pr HESH
Visual range estimation	500 yards	97.7%	86.3%
	1000 yards	71.8%	25.0%
	1500 yards	36.2%	5.1%
	2000 yards	14.5%	1.3%
Metre-base rangefinder	500 yards	98.7%	98.7%
	1000 yards	83.4%	65.3%
	1500 yards	55.5%	23.5%
	2000 yards	28.6%	7.1%

DISCUSSION AND CONCLUSIONS

49. It is not within the scope of this report to do more than comment briefly on the results of the calculations reported above.

* The angle subtended by one-half this target at the gun is $8/\pi = 2.546$ m for 500 yards range, and proportionally less at other ranges.

50. It will be noted that the chances of hit quoted are in general considerably lower than those that have often been though to apply in the past. It is however considered that the values given in this report agree much more exactly with those likely to be obtained under actual battle conditions; in fact, the whole aim of this exercise, and of the concept of quasi-battle conditions, is to attempt to obtain values that are as realistic as possible. It is perhaps worth mentioning here that the figures quoted for chances of hit are, of course, average figures taken over many tanks firing on many occasions; a particular tank firing in a particular action may either do better or worse than this expected value.

51. An examination of Tables 18-21 shows that certain component errors are dominant in determining the chance of hit that is obtained. In particular, the permanent biases, the shooting-in and alignment errors, the rangefinding error in elevation, and the error in line due to trunnion tilt must be cited. For the lower velocity HESH ammunition, errors due to cross-wind and drift are important at the longer ranges. The methods that might be used to decrease the values of some of these errors will form the subject of further work and will not be further considered here; the chance of making reasonable improvements seem good, however.

52. In conclusion, however, it may be mentioned that while methods of improving the first-round chance of hit are obviously of the utmost importance, the time within which a hit (and kill) can be obtained must also be kept to a minimum. These considerations are reflected in the recently agreed tripartite statement on gun accuracy which reads "The ultimate engagement objective for light, medium and heavy gun tanks is to achieve, with a given load of ammunition, the largest number of successful engagements each in the shortest possible time" (39).

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Table 18

Summary of errors in Centurion 20 pr QF gun (mils at gun)

APDS - ELEVATION

	Error	500^x	1000^x	1500^x	2000^x
Permanent bias	Mean jump	0	0	0	0
	Sight off-set	-0.637	0	+0.212	+0.318
	Range graduation	-	-	-	-
	Bias in rangefinding	-	-	-	-
	Sum of biases	-0.637	0	+0.212	+0.318
Variable bias	Shooting-in error	0.516sd	0.516sd	0.516sd	0.516sd
	Alignment	0.337sd	0.337sd	0.337sd	0.337sd
	Mech errors in sighting system	0.045sd	0.044sd	0.045sd	0.046sd
	Jump, occ-to-occ	-	-	-	-
	Droop, occ-to-occ	0.296sd	0.296sd	0.296sd	0.296sd
	Co	0.002sd	0.005sd	0.011sd	0.021sd
	Gun wear	-0.013	-0.025	-0.040	-0.055
	Charge temp, occ-to-occ	0.008sd	0.016sd	0.027sd	0.036sd
	Head-wind	-	-	-	-
	Rangefinding: Visual	0.336sd	0.709sd	1.103sd	1.554sd
	RF	0.011sd	0.048sd	0.108sd	0.202sd
	Discrete range intervals	0.065sd	0.068sd	0.071sd	0.075sd
	Sum of biases	-0.013	-0.025	-0.040	-0.055
	Total sd: Visual	0.766sd	0.988sd	1.301sd	1.701sd
	RF	0.688sd	0.690sd	0.698sd	0.720sd
Random error and dispersion	Ballistic error	0.276sd	0.276sd	0.276sd	0.276sd
	Propellant, lot-to-lot	0.008sd	0.014sd	0.024sd	0.033sd
	Charge temp, rd-to-rd	0.002sd	0.004sd	0.007sd	0.010sd
	Lay, rd-to-rd	0.119sd	0.119sd	0.119sd	0.119sd
	Backlash in sight/gun	-	-	-	-
	Gustiness	-	-	-	-
	Total sd	0.301sd	0.301sd	0.302sd	0.303sd
	TOTAL BIAS	-0.650	-0.025	+0.172	+0.263
	TOTAL SD: Visual	0.823sd	1.033sd	1.336sd	1.728sd
	RF	0.751sd	0.753sd	0.761sd	0.781sd

Table 19

Summary of errors in Centurion 20 pr QF gun (mils at gun)

APDS - LINE

Error		500^x	1000^x	1500^x	2000^x
Permanent bias	Mean throw-off	0	0	0	0
	Sight off-set	L1.046	L0.296	L0.047	R0.079
	Drift	L0.041	0	R0.043	R0.087
	Sum of biases	L1.087	L0.296	L0.004	R0.166
Variable bias	Shooting-in error	0.455sd	0.455sd	0.455sd	0.455sd
	Alignment	0.345sd	0.345sd	0.345sd	0.345sd
	Throw-off, occ-to-occ	-	-	-	-
	Lateral bend, occ-to-occ	0.074sd	0.074sd	0.074sd	0.074sd
	Trunnion tilt	0.094sd	0.194sd	0.298sd	0.410sd
	Cross wind	0.010sd	0.023sd	0.033sd	0.047sd
	Total sd	0.584sd	0.606sd	0.649sd	0.849sd
Random error or dispersion	Ballistic error	0.246sd	0.246sd	0.246sd	0.246sd
	Lay, rd-to-rd	0.148sd	0.148sd	0.148sd	0.148sd
	Backlash in sight/gun	-	-	-	-
	Gustiness	0.012sd	0.028sd	0.041sd	0.058sd
	Total sd	0.287sd	0.288sd	0.290sd	0.293sd
	TOTAL BIAS	L1.087	L0.296	L0.004	R0.166
	TOTAL SD	0.651sd	0.671sd	0.711sd	0.898sd

Table 20

Summary of errors in Centurion 20 pr QF gun (mils at gun)

HESH - ELEVATION

	Error	500x	1000x	1500x	2000x
Permanent bias	Mean jump	-0.052	-0.052	-0.052	-0.052
	Sight off-set	-0.637	0	+0.212	+0.318
	Range graduation	-	-	-	-
	Bias in rangefinding	-	-	-	-
	Sum of biases	-0.689	-0.052	+0.160	+0.266
Variable bias	Shooting-in error	0.516sd	0.516sd	0.516sd	0.516sd
	Alignment	0.337sd	0.337sd	0.337sd	0.337sd
	Mech errors in sighting system	0.045sd	0.055sd	0.074sd	0.103sd
	Jump, occ-to-occ	-	-	-	-
	Droop, occ-to-occ	0.296sd	0.296sd	0.296sd	0.296sd
	Co	0.013sd	0.050sd	0.127sd	0.271sd
	Gun wear	-0.082	-0.183	-0.308	-0.465
	Charge temp, occ-to-occ	0.005sd	0.010sd	0.017sd	0.026sd
	Head wind	0.001sd	0.004sd	0.011sd	0.025sd
	Rangefinding: Visual	1.253sd	2.873sd	5.013sd	7.827sd
	RF	0.041sd	0.192sd	0.510sd	1.096sd
	Discrete range intervals	0.241sd	0.277sd	0.322sd	0.377sd
	Sum of biases	-0.082	-0.183	-0.308	-0.465
	Total sd: Visual	1.448sd	2.967sd	5.072sd	7.871sd
	RF	0.728sd	0.766sd	0.924sd	1.377sd
Random error or dispersion	Ballistic error	0.296sd	0.296sd	0.296sd	0.296sd
	Propellant, lot-to-lot	0.008sd	0.023sd	0.038sd	0.053sd
	Charge temp, rd-to-rd	0.003sd	0.006sd	0.009sd	0.014sd
	Lay, rd-to-rd	0.119sd	0.119sd	0.119sd	0.119sd
	Backlash in sight/gun	-	-	-	-
	Gustiness	0.001sd	0.005sd	0.013sd	0.030sd
	Total sd	0.319sd	0.320sd	0.322sd	0.325sd
	TOTAL BIAS	-0.771	-0.235	-0.148	-0.199
	TOTAL SD: Visual	1.483sd	2.984sd	5.082sd	7.878sd
	RF	0.795sd	0.830sd	0.978sd	1.415sd

Table 21

Summary of errors in Centurion 20 pr QF gun (mils at gun)

HESH - LINE

	Error	500^x	1000^x	1500^x	2000^x
Permanent bias	Mean throw-off	R0.163	R0.163	R0.163	R0.163
	Sight off-set	L1.046	L0.296	L0.047	R0.079
	Drift	R0.104	R0.320	R0.577	R0.886
	Sum of biases	L0.779	R0.187	R0.693	R1.128
Variable bias	Shooting-in-error	0.455sd	0.455sd	0.455sd	0.455sd
	Alignment	0.345sd	0.345sd	0.345sd	0.345sd
	Throw-off, occ-to-occ	-	-	-	-
	Lateral bend, occ-to-occ	0.074sd	0.074sd	0.074sd	0.074sd
	Trunnion tilt	0.337sd	0.733sd	1.206sd	1.775sd
	Cross wind	0.120sd	0.255sd	0.399sd	0.574sd
	Total sd	0.678sd	0.966sd	1.395sd	1.952sd
Random error or dispersion	Ballistic error	0.296sd	0,296sd	0.296sd	0.296sd
	Lay, rd-to-rd	0.148sd	0.148sd	0.148sd	0.148sd
	Backlash in sight/gun	-	-	-	-
	Gustiness	0.145sd	0.312sd	0.489sd	0.703sd
	Total sd	0.361sd	0.455sd	0.590sd	0.777sd
	TOTAL BIAS	L0.779	R0.187	R0.693	R1.128
	TOTAL SD	0.768sd	1.068sd	1.515sd	2.101sd

Appendix A

Derivation of Values for shooting-in and alignment errors

Notation

1. σSI - Shooting in error

σAL - Alignment error

σBD - Error due to inaccuracies in boresighting datum points

σBL - Error due to laying the boresight

σCL - Error due to clicker interval of T and A knob

σ J - Error due to occasion-to-occasion variations in jump

σTO - Error due to occasion-to-occasion variations in throw-off

σ D - Error due to occasion-to-occasion variation in droop

σLB - Error due to occasion-to-occasion variation in lateral bend

σCO - Error due to ballistic coefficient, variation in air density

σCT - Error due to charge temperature, variation occasion-to-occasion

σHW - Error due to head-wind

σTT - Error due to trunnion tilt

σ R - Error due to range estimation at T and A

σCW - Error due to cross-wind

σB - Ballistic error

σLL - Error due to lot-to-lot variation in propellant

σT - Error due to rd-to-rd variation in charge temperature

σL - Error due to rd-to-rd variation in lay

σMB - Error due to backlash in sight/gun system

σGH - Error due to gustiness in head-wind

σGC - Error due to gustiness in cross-wind

A superscript as in σHW^1, σTT^1, σCW^1, σGH^1, and σGC^1, refers to the value of these errors under the conditions of zeroing.

Shooting-in error

2. A desirable drill for zeroing the QF 20 pr gun in Centurion is described below. A target with a distinct aiming mark at a known range is used; it is assumed here that, in accordance with current RAC doctrine, this range is 1000 yards.

Appx A

3. The gun and sight are first aligned (T & A'd) as follows. The gun is layed by boresighting through the firing-pin hole to muzzle cross-wires onto the aiming mark; the telescope graticule is then adjusted, using the T & A knobs, with the range-drum set at the T & A mark, until it also is judged to be coincident with the aiming mark. The total misalignment between gun and sight at 1000 yards (the alignment error, σ_{AL}) will therefore be obtained by compounding the errors due to inaccuracies in the boresighting datum points, σ_{BD}, and in laying the boresight*, σ_{BL}, with the errors in laying the telescope graticule, σ_L, and those due to backlash in the sight/gun system, σ_{MB}, and due to the discrete intervals on the T & A knob adjustments**, σ_{CL}. Thus:-

$$\sigma_{AL}^2 = \sigma_{BD}^2 + \sigma_{BL}^2 + \sigma_L^2 + \sigma_{MB}^2 + \sigma_{CL}^2 \quad \ldots\ldots\ldots \text{(i)}$$

4. The next step is to determine the zeroing correction. The appropriate elevation is applied to the gun using the range-drum, and a cleaner round fired. The sight is laid on the aiming mark on the target and an APDS round fired. Two more rounds are then fired, relaying between each, and the position of the MPI on the target estimated from the points of strike of the three rounds. The error in estimating the position of the MPI is obtained by compounding the relevant variable biases and random dispersions; thus if σ_1 is the standard deviation of this error (the zeroing error) in elevation:-

$$\sigma_1^2 = \sigma_J^2 + \sigma_D^2 + \sigma_{CO}^2 + \sigma_{CT}^2 + \sigma_{HW'}^2$$

$$+ \tfrac{1}{3}\left(\sigma_B^2 + \sigma_{LL}^2 + \sigma_T^2 + \sigma_L^2 + \sigma_{MB}^2 + \sigma_{GH}^2\right) \quad \ldots\ldots \text{(ii)}$$

A similar expression holds for the zeroing error in line.

5. The sight is relayed on the aiming mark again, and then adjusted using the T & A knobs onto the estimated position of the MPI of the three shots. The standard deviation, σ_2, of the error in carrying out this part of the drill is given by:-

$$\sigma_2^2 = 2\sigma_L^2 + \sigma_{CL}^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(iii)}$$

6. The amount by which the T & A knobs are moved during this last process is known as the zeroing correction. The error in the value obtained for this correction (that is, the shooting-in error, σ_{SI}) will be obtained by compounding the alignment error, σ_{AL}, with σ_1 and σ_2 just derived. Thus, in elevation,

$$\begin{aligned}\sigma_{SI}^2 &= \sigma_{AL}^2 + \sigma_1^2 + \sigma_2^2 \\ &= \underline{\sigma_{BD}^2 + \sigma_{BL}^2 + 3.33\sigma_L^2 + 1.33\sigma_{MB}^2 + 2\sigma_{CL}^2} \\ &\quad \underline{+ \sigma_J^2 + \sigma_D^2 + \sigma_{CO}^2 + \sigma_{CT}^2 + \sigma_{HW'}^2} \\ &\quad \underline{+ 0.33\sigma_B^2 + 0.33\sigma_{LL}^2 + 0.33\,\sigma_T^2 + 0.33\,\sigma_{GH'}^2} \quad \ldots\ldots \text{(iv)}\end{aligned}$$

---

* There is evidence (37) that the value of the combined error $(\sigma_{BD}^2 + \sigma_{BL}^2)^{\frac{1}{2}}$ is of the order of 0.296ɱ (1.00')sd; this value is used in this report.

** The clicker interval on Centurion sight is 0.338ɱ (1.14'); hence σ_{CL} has been taken to be $0.338/\sqrt{12} = 0.098$ɱ sd (as is usual for a rectangular distribution (17)).

Similarly, in line,

$$\sigma_{SI}^2 = \underline{\sigma_{BD}^2 + \sigma_{BL}^2 + 3.33\sigma_L^2} + \underline{1.33\sigma_{MB}^2 + 2\sigma_{CL}^2}$$
$$\underline{+ \sigma_{TO}^2 + \sigma_{LB}^2 + \sigma_{TT'}^2 + \sigma_{CW'}^2}$$
$$\underline{+ 0.33\sigma_B^2 + 0.33\sigma_{GC'}^2} \quad \ldots\ldots\ldots \text{(v)}$$

Alignment error

7. An expression has already been given for the value of the alignment error to be adopted for the shooting-in procedure. On a subsequent occasion, when gun and sight are T & A'd, the error in elevation must be taken as slightly greater as it is unlikely that the range to the target will be exactly the same as that to the target used when shooting-in. A small error, σ_R, is therefore included to cover this; an s.d in range difference of 20 yards at 1000 yards (equivalent to 0.050₥ at the gun) has been taken as a reasonable estimate of this error. Thus, in elevation,

$$\sigma_{AL}^2 = \underline{\sigma_{BD}^2 + \sigma_{BL}^2 + \sigma_L^2 + \sigma_{MB}^2 + \sigma_{CL}^2 + \sigma_R^2} \ldots\ldots\ldots \text{(vi)}$$

In line, the error is given by equation (i)

Values for shooting-in and alignment errors

8. Values for the shooting-in and alignment errors for Centurion have been calculated using the expressions given above. The magnitudes of the component errors have already been given, in the majority of instances, in the body of the text or in this Appendix. As has already been implied, however, certain of the errors have values for the conditions of zeroing which are different from those which apply in action. In particular, because it is usual for an especial effort to be made to stand the tank on a level piece of ground when zeroing, and also because zeroing is only carried out on a day in which the wind is considered moderate, the following values have been taken for the errors due to trunnion tilt and wind when zeroing (with APDS) at 1000 yards:-

Error due to trunnion tilt when zeroing ($\sigma_{TT'}$) = 0.039₥ (0.132') sd
(based on sd of trunnion tilt of 1.0° (27))

Error due to head-wind when zeroing ($\sigma_{HW'}$) : negligible

Error due to cross-wind ($\sigma_{CW'}$) : 0.020₥ (0.068') sd
(based on sd of wind velocity of 4.2ft/sec (29))

Error due to gustiness in head-wind ($\sigma_{GH'}$) : Negligible

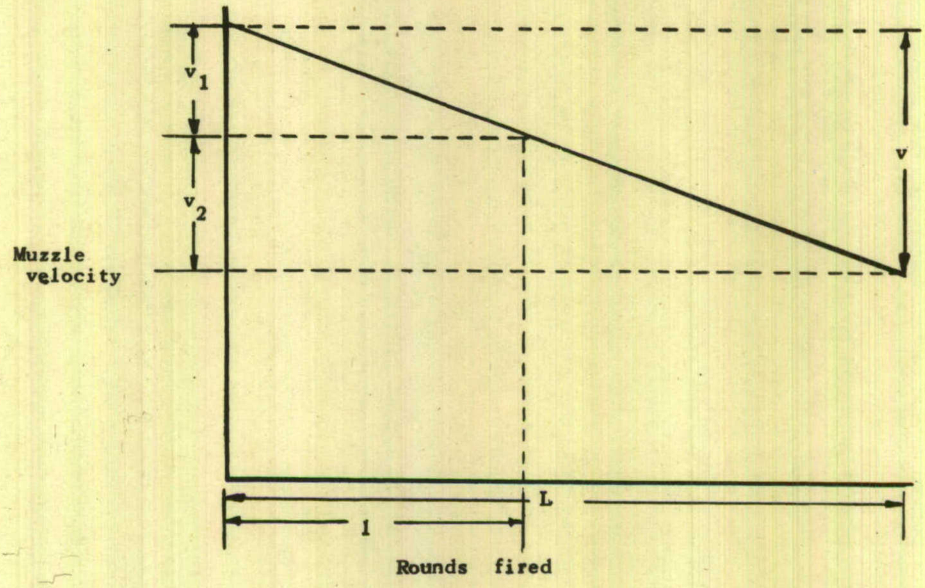
Error due to gustiness in cross-wind ($\sigma_{GC'}$) : 0.028₥ (0.094') sd
(based on sd of gust velocity of 5.9 ft/sec (29))

In addition, the error in laying against a distinct target with a definite aiming mark has been taken as 0.059₥ (0.20') sd in both line and elevation (for the X6 telescopic sight) - see para 43.

Appendix B

Estimation of bias due to gun wear

1. There is an approximately linear drop in muzzle velocity over the life of a gun; this is shown diagrammatically in the figure below where v is the velocity drop over the gun life L rounds



2. It can be assumed that whenever a new barrel is mounted in a tank it will be zeroed before the tank is in action. An opportunity may not arise for the gun to be zeroed again during the course of its life; if, however, there is a chance of zeroing subsequently, this will naturally be taken. It seems unlikely under present circumstances that the gun will be zeroed more than once subsequent to its initial zeroing.

3. Assume that this second zeroing takes place when l rounds have been fired. Then the average drop in MV since first zeroing is given by:-

$$\tfrac{1}{2} v_1 = \tfrac{1}{2} lv/L$$

Similarly, the average drop in MV over the remaining (L - l) rounds of the gun's life since the second zeroing is given by:-

$$\tfrac{1}{2} v_2 = \tfrac{1}{2} (L - l)\, v/L$$

Hence the average drop in MV for all rounds, $\bar{v}$, is given by:-

$$L\bar{v} = \tfrac{1}{2}\, l\, v_1 + \tfrac{1}{2}\, (L - l) v_2$$

$$\text{or } \bar{v} = (l^2 + (L - l)^2) v/2L^2$$

4. For present purposes, it will be assumed that the gun is not used after the third quarter, and is either only zeroed once at the beginning of its life or is, in addition, zeroed at the commencement of the 2nd or 3rd quarters of life; each of these occurrences is assumed to be equally probable. Using an approach similar to that outlined above it is found that $\bar{v} = 19v/72 = v/4$ (approx).

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R.W.Shephard, S.A.Beach.

Feb. 1958

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